

The University of Chicago

FIELD AND LABORATORY STUDIES
OF NON-CONCENTRIC
FOLDING

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1939

By
HARRISON WILSON STRALEY III

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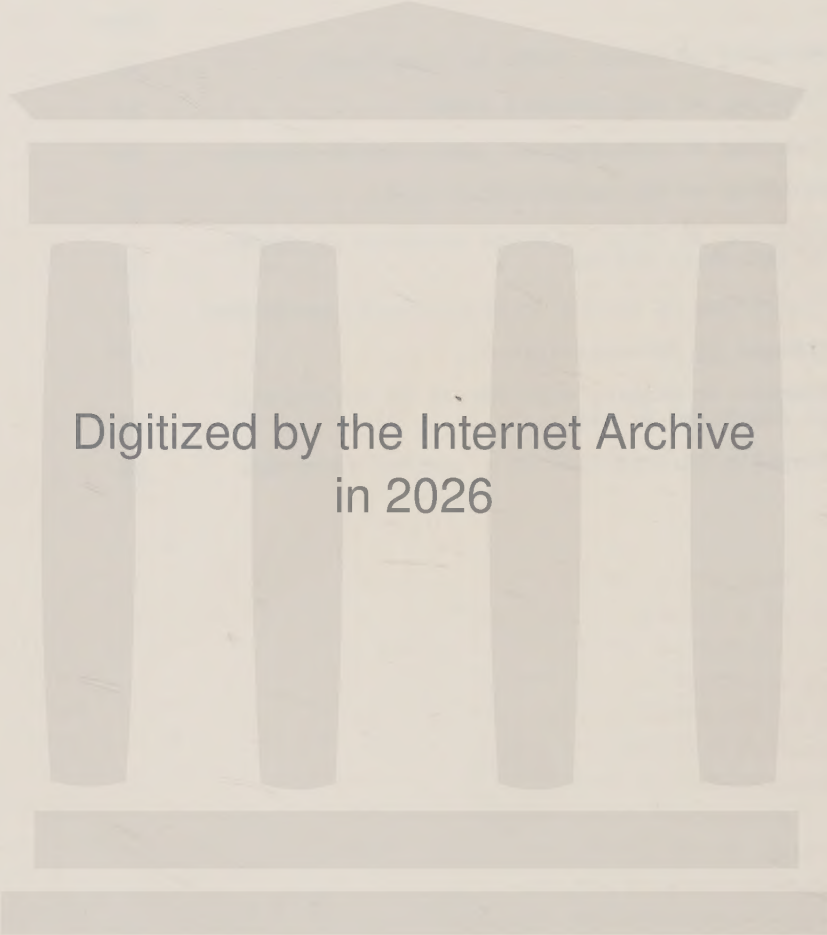


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FIELD AND LABORATORY STUDIES OF NON-CONCENTRIC FOLDING

Abstract

Experiments similar to those of Willis were performed under slightly better controlled conditions of strength of materials and pressure. The relationship between stratigraphic thickness and deformation was compared graphically with data obtained by direct field observation. A surprisingly close agreement was found.

The conclusion is drawn that apparent thickening of crests of anticlines and thinning of limbs has been accomplished mainly by differential compaction in the early stages of deformation; recrystallization where present became important in late folding.

The writer believes that adjustment has been accomplished in the folds under consideration by shear-flow more than by recrystallization. He presents evidence to show that contrary to a widely held view shear-flow is not a phenomenon of great depth but may occur within 7,500 feet of the surface of the earth.

Introduction

This study was undertaken originally for the purpose of developing a formula to express the stratigraphic thickness¹ of strata at depth in non-concentric folds from a knowledge of the surface thickness and structure. After several months of investigation it was found advisable to abandon the original purpose and to concentrate on the process by which thickening and thinning are accomplished and to confine attention to minor folds.

Although drill-core and mine measurements of coal beds were available, it was found inadvisable to use them because depositional irregularities of the coal and adjoining strata are so great

¹According to Rubey (1926, p. 336), the stratigraphic thickness may be defined as "the measurement of the strata made at right angles to the bedding."

that the problem of determining the amount of deformative change in stratigraphic thickness is very difficult. An example of this variation is given by Wentworth (1922, chart opp. p. 16) from Russell County, Virginia, where the Jawbone and Tiller coals, elsewhere separated by an interval of about 50 to 100 feet, unite east of Wilder to form a single seam. The amount of compaction prior to folding could not be determined and will be shown, in a forthcoming paper, to be areally variable. Correlation of test borings is imperfect, except over small areas. An example appears in Russell County, Virginia (Wentworth, 1922, chart opp. p. 24), where the Tiller coal of bore hole number 10, which underlies the Jawbone of the same and previous holes, was correlated with the Jawbone of bore holes number 48 and following. The use of such faulty correlations would lead to erroneous conclusions.

Acknowledgments

To R. T. Chamberlin and F. J. Pettijohn the writer is under obligations for advice and encouragement throughout this investigation. C. H. Behre, Jr., has given advice on field methods and locations for study; F. P. Shepard and M. K. Hubbert have advised on laboratory technique. R. M. Lambie, former chief of the West Virginia Department of Mines, placed the facilities of that organization at his disposal, and the entire staff rendered willing assistance. Numerous mine owners, superintendents, managers, and engineers have been extremely kind in permitting examination of their properties, logs of test borings, and mine maps. Among these the writer wishes especially to mention T. H. Clagett, the late J. E. Jones, Alex Lang, J. J. Lincoln, and R. N. Nowlan.

Previous Work

Heim (1878, pp. 31-32), who first recognized that changes in the geometrical form of beds may take place without notable fracture, says:

In the close examination of many folded or squeezed strata, veins and open fractures are so seldom to be seen that we cannot possibly attribute the deformation to that kind of displacement. . . . Bending, stretching, thickening, rolling out, and shearing are commonly related. . . . Deformation without fracture is an effect of higher mechanical stresses than deformation with fracture.

Willis (1893, pp. 213-284) made an experimental and theoretical analysis of folding, and in his revised textbook sets

forth the mechanics of incompetent structures. He believes that non-concentric folds are the result of radial compression and that the thinning of the limbs is due largely to the pressure of a competent layer on incompetent beds beneath.

Incompetent folding is the result of a deflecting pressure which is initially directed at right angles to the strata, or nearly so, when they are in a horizontal or gently inclined position, and which also is resolved into components at right angles and parallel to the stratification. But, since the angle which the direction of the stress makes with the bedding is a high angle, the perpendicular component is larger than the parallel component. Hence, it follows that the mass as a whole is subjected to vertical, or radial compression and to horizontal, or tangential tension. . . . Hence the stress transmitted by the stratum will not be so great on the axis as nearer the source of active pressure, and the maximum lift will be shifted from the axis onto the limb toward the source. The effective force of deformation will be localized at the point of inflection. (Willis and Willis, 1929, p. 257, p. 263.)

Van Hise (1896, p. 600) investigated thickening and thinning in the Lake Superior pre-Cambrian.

Even where the folding is only moderately close the limbs of the folds may be only one-half as thick as the troughs and crests. Where the folding is very close the troughs and crests must be several times as thick as the limbs in order that they may have similar form.

He thought that the adjustments could be accomplished only by plastic flow of the material of the limbs toward the area of relief.

Adams and his associates (Adams and Nicholson, 1901; Adams and Coker, 1910; Adams and Bancroft, 1917) have investigated experimentally the deformation of many kinds of rocks and minerals under a wide variety of temperature and pressure conditions. They have not, so far as the writer is aware, determined the method of flowage of the sedimentary rocks, with the exception of limestone and dolomite.

Ickes (1923, pp. 575-580) showed how the stratigraphic thickness at depth could be determined from the surface structure. Under certain limiting conditions, he found that folds of this type: (1) persist with depth; (2) have a constant dip along any ordinate;² (3) imply crustal shortening under the action of tan-

²He used a coordinate system in which the abscissa represented length, and the ordinate, thickness parallel with the axial surface of the fold. Both (1) and (2) are inherent from the definition of similar folds.

gential forces; (4) imply that the stratigraphic thickness is a measure of the degree of deformation; (5) imply that more heat is produced in the zones of squeezing on the flanks than in the crests and troughs and that the greatest shear and flow per unit area have taken place there; (6) show that thin layers therein may be under concentric or neutral surface conditions; and (7) should be analyzed further. In a later contribution, Ickes (1925, pp. 451-456) applied graphical integration to the problem of predicting stratigraphic thickness at depth.

Rubey (1926, p. 336) found the stratigraphic thickness of the limbs of similar folds equal to the original thickness³ multiplied by the ratio of shortening⁴ multiplied by the cosine of the angle of dip. He also reached the conclusion (Rubey, 1930, p. 35) that the porosity of a shale varies with: (1) the pressure to which it has been subjected, therefore with the depth of burial; (2) the deformation to which it has been subjected; and (3) the cosine of the angle of dip. He states that the ordinate thickness⁵ at the point of inflection of a limb is equivalent to the original thickness of the stratum before folding. He quotes Sorby (1908, pp. 227-231) and Hedberg (1926, pp. 1057-1058) as having called attention previously to the relation between porosity and pressure, or overburden.

Busk (1929, p. 54) says of similar folds: "There are indeed so many unknown factors and the complete treatment of the problem geometrically becomes so complicated, that in the present stage of our knowledge such treatment is rarely worth while." He thinks that concentric folds are the commonest geometrical form but concurs (Busk, 1926, pp. 9-11) with Ickes (1923, pp. 588-591) that structures often partake of both similar and concentric folding. He agrees with Willis that the forces are concentrated at the point of inflection with a diminution away from the attenuation

³The original thickness may be defined as the thickness before folding or tilting. Rubey used the thickness of the bed at some distance from the disturbance where it was still in a horizontal attitude.

⁴According to Rubey, the ratio of shortening may be defined as the ratio of the original horizontal length of the strata to their horizontal length after folding.

⁵The ordinate thickness may be defined as the thickness parallel with the general trend of the axial surface.

toward the axes (Busk, 1926, p. 55).

Behre (1933, pp. 21-22) made measurements of the stratigraphic thickness and dip of slates and contemplated a complete study of the problem. Other writers have mentioned the problem but, so far as the writer is aware, no complete investigation has been accomplished.

Methods of Study

For the present study, methods resembling those of Willis and others (1893, pp. 213-284; Chamberlin and Miller, 1918, pp. 11-44; Chamberlin and Shepard, 1923, pp. 490-512; McCarthy, 1925, pp. 7-18, and 1928, pp. 51-67) were used, with a pressure box of similar design. The only material modification introduced by the writer was that of using a glass front to the box so that measurements and photographs could be made without stopping compression. Models to be deformed were composed of alternating black and white layers of paraffin mixed with varying amounts of petroleum jelly. The layers containing the largest proportion of paraffin were supposed to represent competent strata, and those predominantly petrolatum were supposed to simulate the strata that would yield by incompetent folding. The models were about 2 feet in length.

The structures examined in the field were approximately 100 feet in cross-section view. The rocks were shales and calcareous shales, whose crushing strength was between 600 and 1500 pounds per square inch. In order to make the experiments nearly accurate dimensionally, the crushing strengths of the model strata were determined; for the competent layers, $1500 \times \frac{2}{100} = 30$ pounds per square inch, and for the incompetent, $600 \times \frac{2}{100} = 12$ pounds per square inch. The constituents were then so $\frac{100}{100}$ mixed that the competent layers would deform under a load of between 25 to 35 pounds per square inch, the incompetent between 10 and 15 pounds.

Field work consisted in measuring the stratigraphic thickness and the attitude of strata involved in incompetent folding. The difficulty in attempting measurements elsewhere than in road cuts and cliff faces, where structures are exposed essentially in cross section, was almost insurmountable. Therefore, all measurements used in the graphs were made of such exposures. Efforts were made to determine the shortening ratio and the original thickness. The latter was determined by direct measurement upon unde-

formed beds away from the disturbed area wherever possible; otherwise, by measuring the ordinate thickness at the point of inflection of the fold. Rock samples were collected wherever and whenever possible so that porosity could be determined.

Porosity (Fig. 7) and stratigraphic thickness (Figs. 1-6) were plotted against the amount of deformation in an effort to correlate these properties with the deformation.

Following a suggestion by Behre, unsuccessful efforts were made to determine whether optical changes had taken place in the deformed experimental layers. It was impossible, however, to prepare thin sections of the soft paraffin layers without producing greater deformation than that produced in the compression chamber.

Experiments similar to those of Daubrée (1879, pp. 460-466) were carried out with unoriented mica fragments embedded in the experimental strata. The purpose of these experiments was to determine whether orientation subparallel with the bedding would result and, also, whether migration of mica particles away from the limbs and toward the crests and troughs would take place.

Through the co-operation of the West Virginia Department of Mines, the writer secured many subsurface measurements from the complete set of well logs within the files of that department. The writer has not made a complete canvass of the literature but wherever possible has used published measurements, for which citation of authority has not seemed necessary.

Experiments of the type herein described have been applied in the past to the solution of many problems of structural geology. As pointed out by Willis (1893, p. 235),

Mechanical laws do not vary with the magnitude of the active forces nor with that of the passive resistances; of a series of strata hundreds of feet thick and of a pile of layers only inches thick, the bending, breaking, or shearing will obey the same laws, if all the factors of pressure and resistance are proportional in each case to the dimensions of the pile, and the similitude of the results will be closer the more exactly the conditions in the one case represent those in the other.

One may draw useful qualitative conclusions from such experimentation. However, the analogy between these experiments and natural conditions, as other writers have frequently pointed out, is not sufficiently exact to warrant their inclusion in future studies of a quantitative nature.

Some of the most obvious and most frequently mentioned

lines along which experiments with the pressure box deviate from the Newtonian law of similarity are:

(1) The compression chamber does not supply even, slow enough pressures to produce frequent adjustments by any means other than some form of fracturing, unless the material being deformed is of almost butter-like consistency.

(2) The materials used usually do not approximate the strength and dimensions of rocks.

(3) The box offers an unyielding bottom, which is not entirely comparable to earth conditions. The writer attempted to overcome this obstacle by introducing a layer of dry St. Peter sand between the model and the floor of the instrument. However, this layer did not entirely eliminate the rigid, unyielding base, and introduced complications peculiar to itself.

(4) The temperature conditions at depth, which must be effective in promoting flow, are not duplicated.

(5) The depth of burial cannot be duplicated, and the pressures produced by several thousands of feet of superincumbent strata cannot be neglected. Even the possibility of variation in the amount of overburden was reduced to a minimum in the experiments herein described because sand was the only material available.

(6) The presence of the pressure block introduces complications not always found in nature. Often the layers thickened near the piston with a progressive decrease in thickening toward the passive end of the box. Frequently this deformation was unaccompanied by any other type of failure. Mead (1920, pp. 506-508) used a rubber sheet coated with paraffin in an effort to eliminate the effects of the piston, but it is doubtful if his apparatus could be used in experiments dealing with the problem under investigation.

(7) The sides of the compression chamber do not permit horizontal adjustments such as probably take place in nature, and there is friction between the sides of the model and the box.

(8) Compaction through loss of porosity in packing particles together may be considerable in sediments. However, in this respect paraffin is a poor substitute for rock. The writer, through direct experimentation, found the volume decrease of paraffin under pressures within the range used in the pressure box negligible.

(9) The intensity of folding is concentrated within a small area in the compression chamber, whereas the forces within the earth act over wide areas.

In view of these considerations, the writer is doubtful of quantitative conclusions predicated upon experiments of this kind and hesitates to attach great significance to them.

When no computations, other than additions of strata thickness, are to be made with a set of measurements, they need not be more accurate than the nearest foot. However, in the investigation herein described computations of ratios were contemplated from the beginning, requiring, therefore, accuracy greater

than in ordinary geologic work. This need for accuracy, necessitating the use of localities where the exposures were in cliff faces and road cuts showing whole structures virtually in cross section, limited the size of fold that could be studied in the field.

Field studies have been made: (1) along U. S. highway 50, from about a mile south of Keyser, West Virginia, to Burlington, Mineral County, West Virginia; (2) along West Virginia highway 24, southwest of Parsons, Tucker County, West Virginia; and (3) along U. S. highway 21, on Brushy Mountain, Bland County, Virginia.

Expression of Results

In Figures 1-4 and 6, the results of the experiments are represented graphically, and in Figure 5 measurements are made on Paleozoic shales. The curves are composites of several methods of expressing the two variables--deformation and change in stratigraphic thickness. Deformation has been represented by the angle of dip, the cosine of the angle of dip, the opening angle⁶ of the fold, the reciprocal of the ratio of shortening (deformed length $\div$ undeformed length), and the logarithm of some of these. The logarithm of the thickness was used as ordinate on a series of graphs.

In plotting measurements made on the crests and in the troughs of the experimental anticlines and synclines the dip was valueless because it was usually almost zero. This necessitated the introduction of the average dip of the limbs and the average thickness of their strata which were considered proportional to the compression.

In the field it was impossible always to determine the original thickness of the strata, so that the thickness of the beds at the crest of the anticlines or at the trough of the synclines was taken as unity in some of the computations. In order to compare the graphs it was necessary to recompute the experimental data on the same basis.

⁶This term was suggested verbally by Behre (1933, p. 157) but had been used previously without definition. In the absence of other information and on the basis of conversation with Behre, the writer offers the following definition: The opening angle may be defined as the angle between the tangents drawn to the curve of a fold at the points of inflection of the limbs.

The impracticability of presenting all the graphical representations used is at once apparent. It has been decided to use dip because it is easily determined in the field or laboratory, and all other measures of deformation are functions of the dip.

In preparing graphs only those observations have been used that were considered reasonably reliable. Many of the layers behaved as competent strata and were folded into nearly concentric folds. In places faults produced supratenuous folds in the superincumbent strata. Often the overburden of sand, or the layer of St. Peter sand beneath, obscured the face of the model so that readings of sufficient accuracy could not be made.

Had the accuracy of the experimental work justified it, the writer would have made a more complete analysis of the observations than appears herein.

Results

Thinning of Limbs

Because of its position in the structure one would expect the middle limb of a fold to have suffered the greatest attenuation. Figure 1 is a composite of all the experimentally developed middle limbs. Although the distribution of the plotted observations was exceedingly poor, there is an indication that thinning in the experiments was nearly completed long before the fold became overturned. There is even a slight rise from the minimum thickness attained, indicating a possible thickening. This is in contrast to conditions described in the Alps and elsewhere, where the middle limbs of many folds are much attenuated and in places completely absent. Of course, most of these descriptions are of folds that have been overturned and are frequently recumbent. In looking for an explanation of the apparent cessation of thinning at such an early stage in the deformation, one is led to believe that the separation of the layers by measurable amounts leaving voids under the troughs of the synclinal areas may be the cause. Such behavior would lead to maximum vertical downward pressures over the crests of the anticlines and to regions of little or no pressure over the troughs of the synclines. The curves for the thickening of the anticlines appear to point toward the same conclusion.

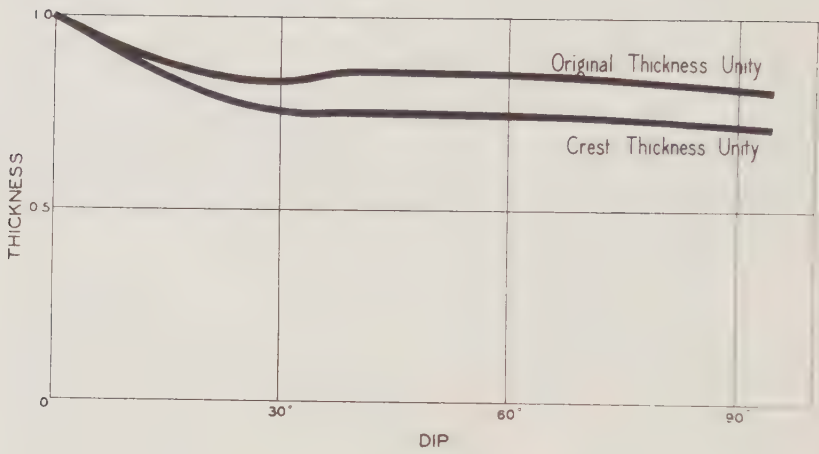


Fig. 1.--Thinning of middle limbs in experiments

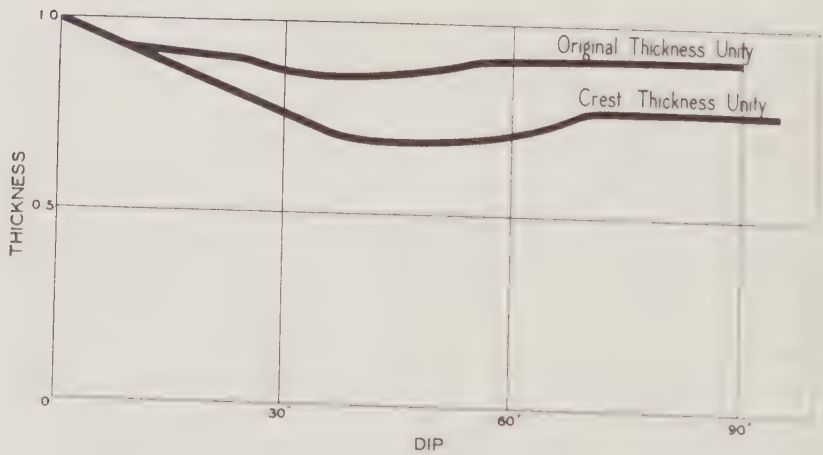


Fig. 2.--Thinning of experimental limbs

The limbs toward the end of the box away from the incoming plunger block are more removed from its disturbing influence than those near the plunger, and their behavior should more nearly approach that of folds in nature.

Figure 2 is a composite of all limbs experimentally developed away from the plunger. A minimum thickness was reached early in the deformation, after which there was an increase in thickness. A similar increase was observed to a lesser extent in the middle limb experiments but is decidedly noticeable in those away from the piston. The explanation is probably the same as that tentatively offered for Figure 1.

The limbs toward the plunger are more subject to its disturbing influence than those farther removed. However, it was from observations upon this limb that Willis (1893) deduced the mechanics of incompetent folding.

Figure 3 is a composite of all limbs experimentally developed toward the plunger. The form of the curve is different from that assumed by either of the others and is in agreement with the mechanics previously mentioned. However, it is doubtful if there is always, in nature, a massif comparable to the piston. The explanation of the flat portion of the curve is probably the same as has been tentatively advanced in previous discussions, and that of the secondary thinning appears to be the constantly maintained pressure of the incoming block.

Qualitatively, the graphs of all the limb measurements should throw some light upon the relation between stratigraphic thickness and deformation. They are comparable to the graphs of measurements made in the field, for all the limb measurements were there plotted together.

Figure 4 is a composite of all limb measurements. The form of the curves is similar to that of Figure 3 for the limbs toward the plunger. The downward slope of the curves in their later stages is the result of measurements made upon overturned folds.

The observations recorded in Figure 5 were made on Paleozoic shales in the Appalachian Mountains, either northwest or southeast of the Allegheny front. The overburden at the time of folding in no case is supposed to have exceeded 12,000 to 15,000 feet.

The curve with the crest thickness of the anticline used

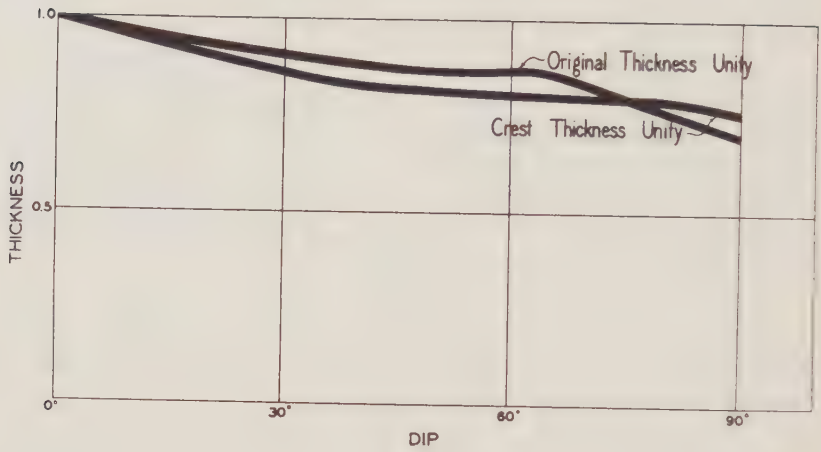


Fig. 3.--Thinning of experimental limbs toward plunger

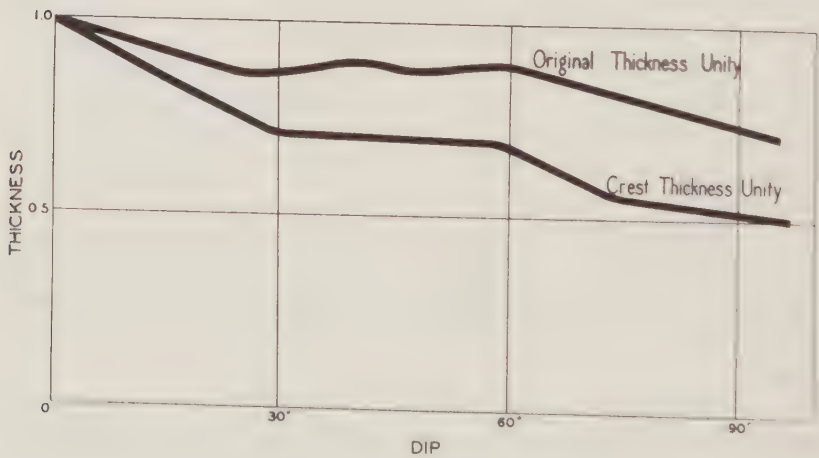


Fig. 4.--Thinning of all experimental limbs

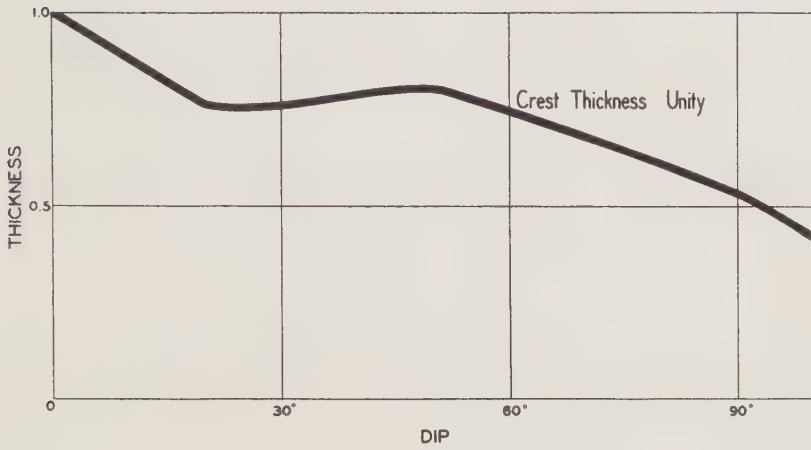


Fig. 5.--Thinning of limbs of folds relative to crests in Paleozoic shales

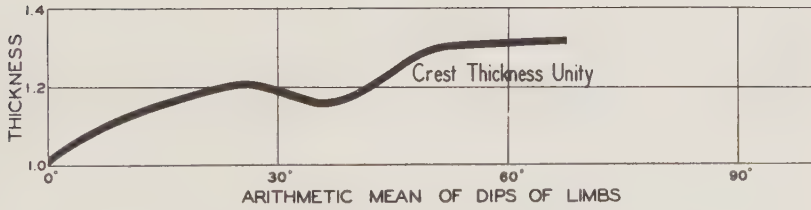


Fig. 6.--Thickening of crests in experimental anticlines

as unity shows a terrace at about 0.8 thickness, which, although slightly higher, is comparable to similar terraces of the experimental graphs.

The similarity between all the graphs lies in the apparent cessation of thinning, followed in turn by renewed thinning with more severe deformation. It is surprising that the range over which the increased deformation brings about no great change in thickness of the limbs is substantially the same in all cases, even in the graphs of published sections. The amount of thinning in that range is approximately the same in all instances.

Thickening of Crests of Anticlines

Figure 6 is a composite of all observations of thickening of crests of the experimentally developed anticlines. There appears to be a terrace at about 1.2 thickness. After more severe deformation, thickening begins again, but the curve is apparently asymptotic to a figure close to 1.3. This is in accord with the results of the limb experiments.

The rigid, unyielding bottom of the box restricted the formation of synclines to the depressions between two anticlinal ridges whose number was limited by the weakness of the material and its inability to transmit stresses. So few points could be determined on synclines that they were not plotted.

Compressibility of Paraffin

Four experiments were performed to determine the compressibility of paraffin. In two, molten paraffin was poured into wooden containers into which pistons could be forced. Beautiful slickensides and shear surfaces, at angles of 45° and 30° to the deforming forces, were produced when the boxes failed. However, the decrease in volume, under pressures comparable to those of the pressure box, was negligible. When iron pipes were substituted for the wooden compression chambers the results were unaltered.

Orientation of Fragments

Flat, unoriented fragments of tin foil and mica were introduced into four models in such a manner that they stood at high angles to the bedding. After deformation, in which there had been transfer of material crestward and troughward, the fragments were recovered. Ten out of eleven had been rotated so as to have their

longest dimension parallel with the lines of flow of the paraffin (Daubree, 1879).

Some of these fragments had moved toward the anticlines from their original position in the limb nearest the piston, and one had retreated toward the anticline from the limb away from the plunger. None moved from an anticline or a syncline toward the limbs. These results may be interpreted as indicating definite movement of material away from the limbs and into the rising anticlines.

Following a suggestion by Behre,⁷ efforts were made to section some of this paraffin to determine its internal structure. These efforts failed because of secondary flowage.

Significance of Graphs

The compressibility of wax, under the action of forces of the magnitude used in the pressure box, has been shown to be negligible. No volume changes could be detected in the experimental structures. But, even in the early stages of deformation, flat, unoriented bodies placed in the wax tended to be rotated into flow lines, and some of them moved anticlineward. These three lines of evidence indicate thickening and thinning by transfer of material.

The rapid initial thickening and thinning were due largely to the pressure of the competent beds in the limbs upon the incompetent ones, after the manner described by Willis (1893). But, as the folds rose higher, the load was transferred from the limbs to the crests through a bridging of the adjacent synclinal areas by the competent layers and the development of voids between the beds beneath the troughs of the synclines. This migration of the point of major stress brought the flowage to a standstill or possibly reversed its direction.

As the ridges rose higher with additional compression, the angle of repose of the overburden was passed. Slipping transferred overburden to the synclinal areas and compacted the model so that the voids were eliminated. After this, the force was transmitted much as it had been in the early stages of deformation, and migration of material from the limbs crestward and troughward was re-established.

⁷C. H. Behre, Jr.: oral communication.

As the anticlinal ridges increased in height, the load on the crests was relieved by the further removal of overburden. In time this permitted the model, acting as a unit, to rise like a wedge through the sand without noticeable deformation.

Volume Changes

Decrease in the absolute volume of a rock stratum may take place in one or both of two ways: (1) by the pressing together of the particles so as to decrease porosity; and (2) by the development of new minerals of higher density--recrystallization. The present study deals entirely with sedimentary rocks, which originally were very porous. According to Nevin and Sherrill (1929, p.6), the greatest compaction of muds always occurs during the early stages, and recrystallization becomes a dominant factor in the final stages.

These volume changes are independent of whether the compaction is due to the overburden or to folding. Of compaction in general, Lindgren (1918, p. 542) says:

It is also well known that diminution of volume may take place in unconsolidated sediments under pressure, by closing of pores and other openings, and by incidental squeezing out of any fluid or gaseous phase which the rock may contain. In such rocks lateral movements of plastic material may occur, though this would only effect a relative change of volume. Similar relative volume changes occur by recrystallization under conditions of rock flowage (as in the case of marble or ice).

That such changes take place through deformation is conceded, and their approximate value in one case is stated by Leith and Mead (1915, pp. 112-113): "Shale changed to slate loses in porosity, but not in mineral gravity. Hence, the volume change is one of pore space. This is on the average 12 per cent." This is in spite of the fact that the chief constituents of slates, however, are essentially porphyroblastic; far from suffering comminution, they have actually been enlarged in size (Behre, 1933, p. 54).

Porosity Determinations

Determinations of the porosity of rock samples were made by the method of Russell (1926, pp. 931-934) and porosity has been plotted against deformation as measured by dip, in Figure 7.

In plotting Figure 7, it was necessary to make small adjustments from structure to structure in order to consider all

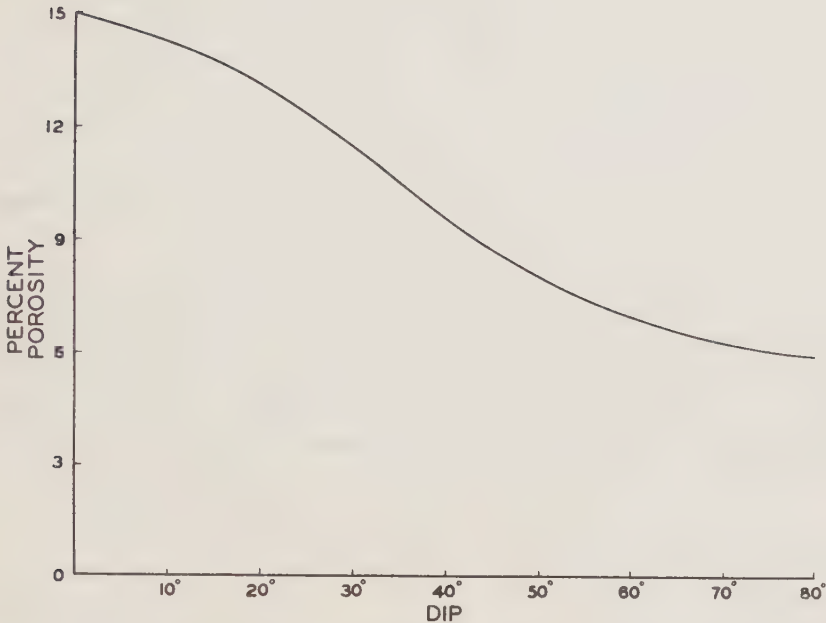


Fig. 7.--Changes in porosity with dip

initial porosities identical--15 per cent. The porosity of the shales was found to be somewhat higher away from the deformed areas than in them, even where the dip was zero in both instances. The writer believes that porosities of samples taken away from the deformed areas represent the effect of overburden only slightly modified by subsequent deformation. On the other hand, specimens secured in the areas of deformation show the effects of the folding stresses to a more marked degree than those from undeformed portions of the same stratum.

Woolard (1938) showed that porosity of shales in the Big Horn region of Montana and Wyoming varied directly with the depth of burial. He made no effort to correlate porosity with deformation as had been done by Rubey (1930, p. 35).

The low porosities determined by the present writer which were rarely greater than 15 per cent do not agree with those of 25 per cent to 37 per cent as determined by Rubey (1930, p. 35). However, they show a depth of burial of the order of magnitude of 7000 to 10,000 feet when compared with Woolard's (1938) curve.

The writer regards this as a satisfactory check on his porosity determinations, in view of the contention that the overburden in the areas studied never exceeded 12,000 feet.

In Figure 7, it may be seen that during the initial stages of deformation, up to dips of about 15° , the decrease in porosity remained nearly constant. For deformations of from 15° to 50° the decline in porosity is more sharp. Above 50° changes in porosity are not so rapid.

In Figure 8, density has been plotted against deformation as represented by dip. From a dip of about 3° onward the density gradually increases to about twenty degrees; whereupon it increases rapidly. This rapid increase continues to about 45° , from which point the increase in density is more gradual. The writer concludes that the density determinations, although few in number, substantiate the evidence derived from porosity.

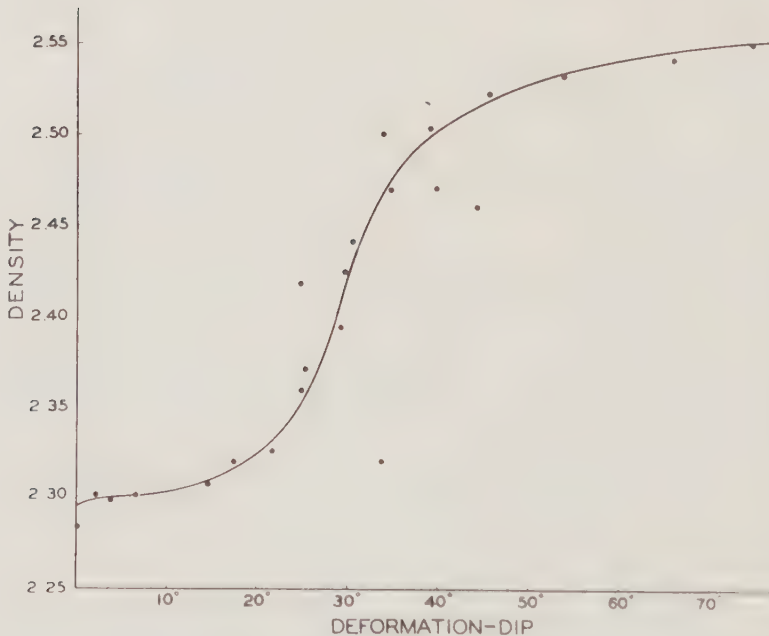


Fig. 8.--Changes in density with degree of deformation as indicated by dip

Figure 9 represents a smoothed porosity curve over one of the structures in Mineral County, which is represented diagrammatically below the curve. It is noteworthy that the porosity maxima occur over the anticlines, the minima over the synclines, and that the flanks of the structure have intermediate porosities. This curve may be taken as typical for all the structures examined.

The explanation of these relationships appears to lie partly in the sampling and partly in the mode of adjustment of the shale to the folding stresses. The samples of rock for examination were always collected from the uppermost part of the layer, which is in tension in the anticlines and in compression in the synclines. Minute fractures in the bed at the anticline resulting from tension would increase the porosity of the rock, while the compression in the synclines would tend to close up pores by pushing the particles together and healing any fractures that might have developed from shear flowage.

The limbs of the folds are, according to Willis (1929), under compression from the pressure of superincumbent, relatively competent strata.

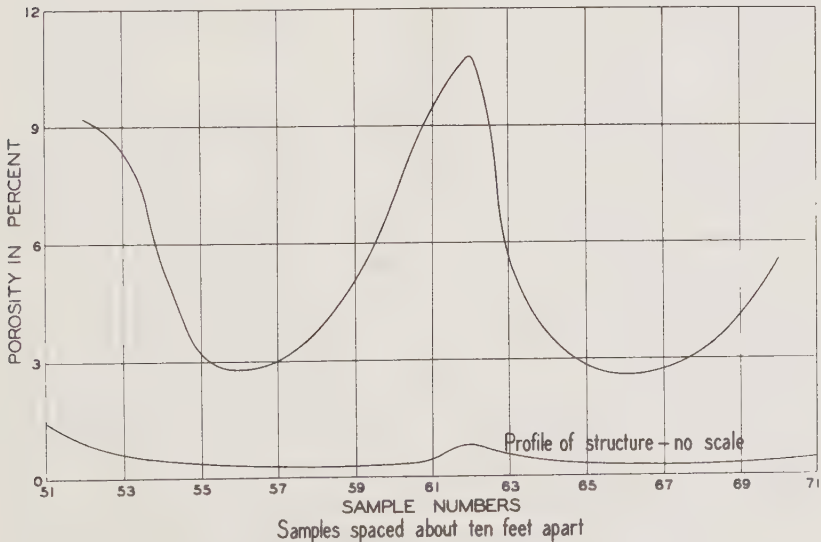


Fig. 9.--Porosity distribution in a typical structure

This compression is undoubtedly severe and tends to compact the particles of rock and, thereby, to decrease the porosity.

On the other hand, if the present writer's contentions are valid, minute shear surfaces developed during flowage tend to remain open and to increase the porosity by an amount sufficient to offset, partially at least, the decrease resulting from compaction of the mineral particles. This is especially true as the development of shear surfaces is supposed to have facilitated flowage away from the limbs and thereby to have reduced the compressive stresses at those places.

Method of Adjustment

General Review

In the section devoted to previous work, the writer mentioned the mechanics of incompetent folding as conceived by Willis (1933), who attributed the thickening and thinning to the pressure of a competent stratum upon the more incompetent strata beneath in the limbs of the fold. Thus a differential compression is introduced, and the rock adjusts itself by thinning under the greater force and thickening under the lesser. Van Hise (1896, p. 600) speaks of the migration of material from areas of slight to those of greater relief of pressure. Baker (in preparation) says that salt and anhydrite flow in similar manner into areas where the superincumbent load is least and, therefore, the relief is greatest. However, it should be recalled that the greatest stress is not always localized at the points of inflection on the limbs, nor the least at the crests or troughs.

It appears probable that the thinning of the limbs of the structures investigated in the shale is largely the result of packing together of particles rather than migration of material, especially during the early stages of deformation. However, these same relations point to a transfer of material from the limbs crestward and troughward at a later period. Thus the two processes operate somewhat simultaneously, the former probably predominant in the early, the latter in the later stages.

These conclusions are in accord with those of Nevin and Sherrill (1929, p. 6) who state that packing of particles together is more important than recrystallization in the early stages of consolidation. They are confirmatory of Rubey's suggestion (1930,

p. 35) that the porosity of shale is proportional to the cosine of the angle of dip.

Mechanism of Thickening and Thinning

Adams, with his associates, has conducted experiments upon a variety of rocks under diverse conditions and has concluded that weak rocks, such as alabaster, steatite, and marble, deform by movements along the gliding planes of minerals, often accompanied by twinning, the movement being similar to that seen in metals when they are deformed. In strong rocks the deformation is accompanied by granulation, the texture developed being similar to mylonite (Adams, 1917, p. 637). Marble columns, which had undergone recrystallization prior to the experiments, adjusted themselves to pressure largely by shearing.

In that portion of the column in which movement has taken place, are certain faint lines which when deformation is slight are just barely perceptible, but which become more pronounced as the deformation increases. These lines are due to a very slight displacement along their course. . . . As the deformation goes forward and becomes more pronounced the movement, while still taking place simultaneously along a great number of these planes, becomes more pronounced along certain of them. The movement in impure magnesian limestone has been of the nature of a complicated shearing.

Sorby (1908, pp. 222-223) and Becker (1893, pp. 13-90) considered flow a continuous shear. Sander (Knopf, 1933, pp. 433-470) considers deformation of this kind to have taken place along parallel slip-planes which may have been developed mechanically by shear. Nadai (1931, p. 76) says that in the plastic state of engineering materials parts of the mass slide with respect to one another simultaneously along countless slip planes.

Bingham (1922, p. 228) says:

A plastic solid is made up of particles which touch each other at certain points. The space between the particles may be empty or it may be filled with gas, liquid, or amorphous solid. Flow necessitates the sliding of these particles the one over the other according to the ordinary laws of friction, so long as the particles are large enough so that their Brownian movement is negligible.

Willis (1929, p. 190) sums up the opinion of many American writers thus:

When a rock mass is forced to shear under great confining stress shearing planes tend to be very closely spaced and the displacements on the very numerous planes are individually small, even though their total may be large. The effect upon the rock is that of flow confined to a thinner or thicker layer.

As previously pointed out, the wax in the writer's experiments migrated into the crests of the anticlines or thickened the layers progressively outward from the plunger. However, no effort was made to determine the mechanism by which this took place. It is extremely doubtful if a knowledge of the manner of wax-flowage would be of assistance in determining the method of rock flow. The possibility of compaction through loss of pore space, for example, is reduced to a minimum in the experimental material, while it is of utmost importance in shale.

In his field work, the writer repeatedly noted small fractures with an orientation essentially parallel with the dip of the beds. Minute displacements had frequently taken place along these fracture lines, which could be detected in the hand specimen with the aid of a lens.

Microscopic examination of the shales revealed numerous shear surfaces roughly divisible into two sets. The less prominent of these is inclined to the bedding and is roughly subparallel with the axial surfaces of the folds. The more prominent set is subparallel with the bedding, and movement appears to have been greater along it than along the other. It seems probable that the chief method of flowage in the shales under consideration was by shearing.

Depth to the Zone of Flow

in Area Studied

Willis (1929, p. 190) expresses the opinion of many geologists when he speaks of shear flow as a phenomenon of depth:

The experiments of Frank Adams, which are described in Chapter xviii, demonstrate the degree of unbalanced pressure necessary to crush minerals under great confining pressure, and indicate that the load must be equivalent to that which the rocks carry at a depth of 30 miles (48 kilometers) below the surface. . . . At much shallower depths local pressures may develop intense stresses that rise to the degree indicated, and mashing probably may occur anywhere below the zone of open fractures, say below 3 to 5 miles (5 to 8 kilometers) provided the opposed stresses are adequately concentrated and take effect before other adjustments can be reached.⁸

⁸ Van Hise (1896, p. 694) defined mashing as follows: "Under mashing is included the process which is usually described in geological writings under the terms dynamic metamorphism and shearing, the authors meaning by the latter differential movement along certain parallel planes."

The writer cannot altogether accept the view that shear-flow is a phenomenon confined to great depths. He can find no mention in the literature of great covering in the areas studied, whereas Campbell (1896, 1925) and Reger (1923, 1926) indicate that only a few thousand feet of superincumbent strata were present at the time of folding. If the interpretation herein set forth is correct, then shear-flow must be a phenomenon of all depths up to a few thousand feet from the surface.

In the area near Parsons the folds are in the Chemung, but for purposes of calculation of overburden at the time of folding the whole of that series has been treated as having been superimposed upon the folded strata:

	<u>Feet</u>	<u>Feet</u>
Dunkard	1000 (approximately)	
Monongahela	204 more than in Tucker County (Martin, 1902, pp. 140-145)	
Exposed in neighboring areas		1204
Monongahela	56 more than at Parsons (Reger, 1926, p. 146)	
Conemaugh	838	
Allegheny	153	
Kanawha	133	
Exposed elsewhere in the county		1180
Pennsylvanian	530	
Mississippian	965	
Catskill	722	
Chemung	2890	
Exposed at Parsons (Reger, 1923, p. 146)		5107
Total maximum cover		7491

The folds in the Mineral County area are all in Chemung⁹ shale, which was treated as superimposed, as in the computations at Parsons.

⁹Log of pre-convention field trip, American Association of Petroleum Geologists' mid-year (Pittsburgh) meeting, 1937, p. 8.

Although Reger (1924, p. 90) apparently does not consider the Dunkard to have been present, it has been included:

	<u>Feet</u>	<u>Feet</u>
Dunkard	.1000	Exposed in Pennsylvania (Martin, 1902, pp. 140-45)
Monongahela	68	Exposed at Lonaconing, Md., in addition to Mineral and Grant cos. exposures (O'Harra, 1900, pp. 128-129)

Exposed outside of Mineral and Grant counties 1068

Monongahela	171	Exposed at Elk Garden
Conemaugh	904	" " Shaw
Allegheny	222	" " Schell
Pottsville	459	" " Bond
Mississippian	.1696	" " Keyser
Catskill	.1925	" " "
Chemung	.4047	" " "

Exposed in Mineral County (Reger, 1924, p. 194) 9424

Total maximum cover 10,492

In the Bland County area, Reger (1926, p. 136) and Campbell (1925, pp. 88-89) doubt the former extension of the Pottsville far east of its present outcrop. Perhaps the Maccrady shale was the youngest formation in this part of the Appalachian geosyncline, and neither the Carboniferous limestone nor the coal-bearing rocks of Pennsylvania age were ever deposited here.

The folds on the slopes of Brushy Mountain are in what Campbell (1896) calls the Kimberling shale, which is upper Devonian. Assuming the Chemung and Portage (upper Devonian) to overlies them entirely, according to previous practice, the thickness of overburden up to and including the Maccrady shale is:

	<u>Feet</u>	<u>Feet</u>
Maccrady	265	Exposed at Bluefield, Mercer Co.
Pocono	390	" " " " "
Chemung	1537	" " Gap Mills, Monroe Co.
Portage	2450	

Exposed in Bland County 4642

	<u>Feet</u>		<u>Feet</u>
Pottsville	545	Exposed at New Richmond, Mercer Co. (Reger, 1925, pp. 271-273)	
Mississippian.	5091	Exposed at Stony Gap, Mercer Co. (Reger, 1925, pp. 271-273)	
Greenbrier	1795	And at Alderson, Monroe Co. (Reger, 1925, pp. 271-273)	
Exposed in neighboring areas			7431
Total maximum cover			12,073

That the writer is not alone in his belief that a transfer of material by what Willis has called "shear-flow" can be accomplished at moderately shallow depths is shown in a study by Wilson (1934, pp. 513-514), who says that rearrangement has been accomplished along many closely-spaced joints in such a way that movement along one joint surface was small but the total amount large. This deformation occurred under a cover of only about 10,000 to 14,000 feet. Behre (1933, p. 51) regards shear-flow as a near-surface phenomenon. He says that, in the absence of moderate overburden, fracture, shear, or flowage without conspicuous recrystallization is likely to occur.

If it is true, as Adams (Adams and Coker, 1910, p. 487) has stated, that flowage with the development of cataclastic structure--shear--takes place where the differential resistance is low, the problem becomes one of finding such places. It is unquestioned that the deeper a rock is buried the greater is the pressure due to overburden. If, as indicated by the Chamberlin hypothesis (1907, 1925), the tangential thrusts are deep-seated, it is likely that a decrease in such forces also takes place surface-ward. If the rate of decrease of load is less than that of thrust, it follows that differential resistance is decreased by approach to the surface. Therefore, the tendency to fail by shearing would be greater at shallow depths.

A number of factors influence the transfer of material (Van Hise, 1904, pp. 737-738) and in all probability modify the mechanism. Some of these factors are: the nature of the rocks themselves, the time involved, the depth of burial, the temperature attendant upon the deformation, the water or oil content of the rocks, the rapidity of the application of the stresses and their magnitude, the porosity of the material, the amount of induration, and the kind of indurating cement.

Conclusions

1. Although there is a tendency for incompetent beds to thin at places of maximum stress and vice versa, the relationship between thickness and degree of deformation is not simple. Other variables, as distribution of competent layers, faulting, heat, induration, intrusions, overburden, time and duration of application of forces, must be given due weight.

2. Future experimentation of a quantitative nature should be confined to methods capable of more exact control than the pressure box.

3. It appears that in the shales under consideration:

- a. Compaction by packing together of shale particles is predominant in the early stages of deformation.
- b. A cessation of the thinning process occurs for a time during the progress of deformation. Thinning may again be resumed with further deformation.
- c. A transfer of material, largely by shear-flow, from areas of high stress to those of low, becomes important in the advanced stages of deformation.
- d. Recrystallization appears to have been of minor importance throughout the entire period of deformation.

4. Shear-flow, instead of being exclusively a phenomenon of considerable depth, is shown to have occurred within less than two miles of the surface of the earth.

Works to Which Reference Is Made

- Adams, F. D., and Bancroft, J. A. (1917) On the amount of internal friction developed in rocks during deformation and on the relative plasticity of different types of rocks, Jour. Geol., vol. 25, p. 637.
- _____, and Coker, E. G. (1910) An experimental investigation into the flow of rocks; First Paper--the flow of marble, Amer. Jour. Sci., 4th ser., vol. 29, p. 467.
- _____, and Nicholson, J. T. (1901) An experimental investigation into the flow of marble, Royal Soc., London, Philos. Tr., Ser. A, vol. 195, pp. 363-401. Cited by Adams and Coker.
- Baker, C. L. (in preparation) On the possible mode of origin of the Big Lime high ridges of the Permian basin.
- Becker, G. F. (1893) Finite homogeneous strain, flow and rupture of Rocks, Geol. Soc. Amer., Bull., vol. 4, pp. 13-90.
- Behre, C. H., Jr. (1933) Slate in Pennsylvania, Pa. Geol. Surv., 4th ser., Bull. M 16, pp. 21-22.
- Bingham, E. C. (1922) Fluidity and plasticity. P. 228. McGraw-

Hill Book Co., New York.

- Busk, H. G. (1929) Earth flexures: their geometry and their representation and analysis in geological section with special reference to the problem of oil finding. P. 54. Cambridge University Press.
- Campbell, M. R. (1896) Description of the Pocahontas sheet. Va. Fol. no. 26, U. S. Geol. Surv.
- _____. (1925) The valley coal fields of Virginia, Va. Geol. Surv., Bull. 25.
- Chamberlin, R. T. (1925) The wedge theory of diastrophism, Jour. Geol., vol. 33, pp. 755-792.
- _____, and Miller, W. Z. (1918) Low angle faulting, Jour. Geol., vol. 26, pp. 11-44.
- _____, and Shepard, F. P. (1923) Some experiments in folding, Jour. Geol., vol. 31, pp. 490-512.
- Chamberlin, T. C. (1907) The fault problem, Econ. Geol., vol. 1, pp. 585-600, 704-724.
- Dale, T. N. (1896) Structural details in the Green Mountain region and in eastern New York, U. S. Geol. Surv., 16th Ann. Rept., pt. 1, p. 567.
- Daubrée (1860) Geologie experimentale. Etudes et expériences synthétiques sur le métamorphisme. Ann. des Mines, 5th ser., vol. 16, pp. 460-466.
- Gilbert, G. K. (1877) Report on the geology of the Henry Mountains, U. S. Geog. Geol. Surv., pp. 80-82.
- Hedberg, H. D. (1926) The effect of gravitational compaction on the structure of sedimentary rocks, Am. Assoc. Petrol. Geol., Bull. 10, pp. 1057-1058.
- Heim, Albert (1878) Mechanismus der Gebirgsbildung, im Anschluss an die Geologie Monographie der Todi-Windgallen, Gruppe Band II Teil, über den Untersuchungen, Seite 31-32.
- Ickes, E. L. (1923) Similar, parallel and neutral surface types of folding, Econ. Geol., vol. 18, pp. 588-591.
- _____. (1925) The determination of formation thickness by the method of graphical integration, Amer. Assoc. Petrol. Geol., Bull. 9, pp. 451-456.
- Joffe, A. F. (1928) The physics of crystals. McGraw-Hill Book Co., New York. P. 49.
- Knopf, E. B. (1933) Petrogenesis, Amer. Jour. Sci., 5th ser., vol. 25, pp. 433-470.
- Leith, C. K., and Mead, W. J. (1915) Metamorphism. Henry Holt & Company, New York. Pp. 112-113.
- Lindgren, W. (1918) Volume changes in metamorphism, Jour. Geol. vol. 26, p. 542.
- MacCarthy, G. R. (1925) Some facts and theories concerning laccoliths, Jour. Geol., vol. 33, pp. 1-18.
- _____. (1928) Experiments in underthrusting, Amer. Jour. Sci. 5th ser., vol. 26, pp. 51-67.
- Mead, W. J. (1920) Notes on the mechanics of geologic structures, Jour. Geol., vol. 28, pp. 506-508.

- Nadai, A. (1931) Plasticity. McGraw-Hill Book Co., New York, P.76.
- Nevin, C. M., and Sherrill, R. E. (1929) Studies in differential compaction, Amer. Assoc., Petrol. Geol., Bull., vol. 13, pt. 1, p. 6.
- O'Harra, C. C., et al. (1900) The geology of Allegheny County, Md., Geol. Surv., pp. 128-129.
- Reger, D. B. (1923) Tucker County, W. Va. Geol. Surv.
- _____ (1924) Mineral and Grant counties, W. Va. Geol. Surv.
- _____ (1926) Mercer, Monroe and Summers counties, W. Va. Geol. Surv.
- Rubey, W. W. (1926) Determination and use of thickness of incompetent beds in oil field mapping and general structural studies, Econ. Geol., vol. 21, p. 336.
- _____ (1930) Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills Region, U. S. Geol. Surv., Prof. Paper 165, p. 35.
- Russell, W. L. (1926) A quick method for determining porosity, Amer. Assoc. Petrol. Geol., Bull. 10, pp. 931-934.
- Sorby, H. C. (1908) On the application of quantitative methods to the study of the structure and history of rocks, Geol. Soc. London, Quart. Jour., vol. 64, pp. 227-231.
- Van Hise, C. R. (1896) Principles of North American pre-Cambrian geology, U. S. Geol. Surv., 16th Ann. Rept., p. 600.
- _____ (1904) A treatise on metamorphism, U. S. Geol. Surv., Mon. 47, pp. 737-738.
- Wentworth, C. K. (1922) The geology and coal resources of Russell County, Virginia, Va. Geol. Surv., Bull. 22, correlation chart facing p. 16.
- Willis, Bailey (1893) The mechanics of Appalachian structure, U. S. Geol. Surv., 13th Ann. Rept.
- _____, and Willis, Robin (1929) Geologic structures. McGraw-Hill Book Co., Rev. ed., New York. Pp. 257, 263.
- Wilson, C. W., Jr. (1934) A study of the jointing in the Five Springs Creek area, east of Kane, Wyoming, Jour. Geol., vol. 13, pp. 513-514.
- Woolard, G. P. (1938) The effect of geologic corrections on gravity anomalies, Trans. Amer. Geoph. Union, vol. 19, pp. 85-91.

